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Znanstveni časopis *Hrvatski meteorološki časopis* nastavak je znanstvenog časopisa *Rasprave* koji redovito izlazi od 1982. godine do kada je časopis bio stručni pod nazivom *Rasprave i prikazi* (osnovan 1957.). U časopisu se objavljuju znanstveni i stručni radovi iz područja meteorologije i srodnih znanosti. Objavom rada u Hrvatskom meteorološkom časopisu autori se slažu da se rad objavi na internetskim portalima znanstvenih časopisa, uz poštivanje autorskih prava

Scientific journal *Croatian Meteorological Journal* succeeds the scientific journal *Rasprave,* which has been published regularly since 1982. Before the year 1982 journal had been published as professional one under the title *Rasprave i prikazi* (established in 1957). The *Croatian Meteorological Journal* publishes scientific and professional papers in the field of meteorology and related sciences.
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Doktorska disertacija – Sažetak
D.Sc Thesis – Extended abstract

OBILJEŽJA TUČE U SADAŠNJIM I BUDUĆIM KLIMATSKIM UVJETIMA NA PODRUČJU HRVATSKE

Hail characteristics in present and future climate over Croatia

DAMJAN JELIĆ

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Sažetak: Tuča je jedna od ekstremnih meteoroloških pojava koja često uzrokuje značajne materijalne štete. Šteti je podložno gotovo sve, a kako raste veličina zrna tuče, tako je razmjer štete sve veći. Izraženije epizode tuče mogu proizvesti štete veće od milijardu dolara, a prema podatcima za Hrvatsku, u razdoblju od 1981. do 2012. godine, oluje i tuča uzrokovale su približno 21 % ukupno zabilježenih šteta nastalih prirodnim nepogodama. Kako bi se na taj problem odgovorilo, proteklih nekoliko desetljeća u Europi, ali i svijetu, raste broj istraživanja usmjerenih na bolje razumijevanje tuče i njenih svojstava pa je tako i cilj ovog istraživanja pridonijeti boljem poznavanju tuče na području Hrvatske. Korištenjem opaženih podataka o tuči sa 186 postaja Državnog hidrometeorološkog zavoda diljem Hrvatske te promatranjem razdoblja od preko 50 godina, provedena je sveobuhvatna klimatološka analiza svojstava tuče. Zatim se uparivanjem dobivenih podataka o tuči i reanalize ERA5 dobila veza sinoptičkih i mezoskalnih uvjeta, a daljnjom obradom regionalnih klimatskih modela iz inicijative EURO-CORDEX i projekcija pojavnosti tuče u 21. stoljeću. Također, na osnovu mjerenja munja razvijen je algoritam za izračun indeksa intenziteta munja koji ističe područja s izraženom aktivnošću oborine, pojavom tuče te udarima vjetra.

Glavni rezultati ovog istraživanja su sljedeći:
1. Prepoznata su tri različita tipa postaja u smislu godišnje dinamike tuče. Unutar Hrvatske razlikuje se „ljetni“ tip postaja koje tuču uglavnom bilježe tijekom toplog dijela godine, suprotni tj. „zimski“ tip postaje te „prijelazni“ tip koji bilježi podjednaku aktivnost tuče tijekom cijele godine. Odvojenim promatranjem navedenih tipova postaja ustanovljeno je da se i dnevni hodovi tuče značajno razlikuju, pri čemu je najinteresantniji „zimski“ tip koji maksimum aktivnosti tuče bilježi u 8 h ujutro.
2. Glavno obilježje tuče je velika prostorna i vremenska varijabilnost na svim promatranim skalama, što potvrđuju i različiti trendovi za različite tipove postaja te različite sezone.
3. U budućoj se klimi očekuje pad aktivnosti tuče za oko 8 %.
4. Indeks intenziteta munja pokazao se vrlo uspješan u prostornoj i vremenskoj identifikaciji intenzivne oborine i tuče. Zbog svoje prirode indeks homogeno popunjava prostor na rezoluciji 3 km × 3 km te nudi visoku vremensku rezoluciju (2 min). Stoga ga je moguće koristiti za identifikaciju kratkoživućih, lokalnih grmljavinskih oluja koje su praćene potencijalno opasnim vremenskim događajima.

Extended abstract:
1. Introduction

Most hail properties, such as its annual and diurnal cycles, trends, and interannual and seasonal variations, can be identified through hail climatology. To date, hail climatology at local or national scales has been analyzed for most European countries (Punge and Kunz, 2016). Data used in derivations of hail climatology include hailpad measurements (Manzato, 2011; Počakal et al., 2009; Sánchez et al., 2009), station measurements (e.g., Burceaetal., 2016; Ćurić and Janc, 2016; Kotinis-Zambakas, 1989; Vinet, 2001; Zhang et al., 2008), hail reports (e.g., Dessens, 1986; Tuovinen et al., 2009; Webb et al., 2001, 2009), radar estimates (Lukach et al., 2017; Nisi et al., 2016; Strzinar and

Skok, 2018; Visser and van Heerden, 2000), satellite assessments (Punge et al., 2017), insurance damage data (Vinet, 2001), and global model outputs (Brooks et al., 2003; Hand and Cappelluti, 2011). Overall, the results show the presence of hail over much of Europe from the northern regions of Scandinavia (up to 67.5°N), where the hail season is shortest (during summer) (e.g., Tuovinen et al., 2009), to the Mediterranean region, where hail can occur throughout the year (e.g., Baldi et al., 2014; Berthet et al., 2011; Punge and Kunz, 2016). In addition, while continental regions are mainly affected by hail during the warmer parts of the year (e.g., April–September), coastal (maritime) regions along the Atlantic Ocean or Mediterranean show different hail frequency distributions. For coastal hail climatology, most cases occur during winter and spring but with relatively few hailstones (Punge and Kunz, 2016; Santos and Belo-Pereira, 2019). According to Punge et al. (2014), the areas with the most frequent hail events are positioned between 39°N and 50°N. Hail hot spots are found in perialpine regions of the north and south, followed by the greater Pyrenees Region, Massif Central in France, Apennines in Italy, Dinarides in the Southeast Europe, and Carpathians in the Pannonian Basin. Some reported hail frequencies have presented values of 0–2,4 hail days per year according to station measurements (Punge and Kunz, 2016), while radar-based estimates have reported values of 0–2 hail days per year (Nisi et al., 2016; Strzinar and Skok, 2018). A recent publication by Punge et al., (2017) provides an estimation of hail frequencies from satellite-based overshooting tops (OTs) and ERA-Interim reanalyses of Europe. The authors reported 10 km × 10 km gridded information for yearly hail frequency estimates that spanned from 0 to 2 hail days (Punge et al., 2017; their Fig. 6) and the spatial distributions corresponded well with previous studies. While Croatia is situated in an area where strong impacts of hail are expected (e.g., Punge et al., 2014), the Adriatic coast has never been analyzed in detail, and its national hail climatology has not yet been developed. Nevertheless, several papers have addressed the hail characteristics of the continental region of Croatia which is an agricultural region that is well equipped with weather radars, meteorological stations, and hailpad networks. The hail properties and their characteristics in the continental part of Croatia are reported in Počakal and Štalec (2003) and Počakal et al., (2009, 2018). In these papers, the analyses focused on the warm season (i.e., May–September), which is connected with the hail suppression network and hailpad data. The main results show that the spatial and temporal characteristics of hail in the period from 1981 to 2006 show higher hail activity on the windward slopes of mountains. The hail frequencies in Croatia range from 0.1 to 2.4 hail days/season. The first 3 months of the hail season represent 84% of total hail cases, and hail is most active between 14 and 18 h local time. Various trend analysis have been made both in Croatia (Gajić-Čapka and Zaninović, 1993) and worldwide (Raupach et al., 2021) but there was no clear conclusion.

Thunderstorms can produce severe weather, such as heavy rain, large hail, wind gusts, tornadoes and cloud-to-ground lightning, which can cause significant damage and can endanger human lives (Hoeppe, 2016). Usually, these thunderstorms have large spatial and temporal scales, such as mesoscale convective systems (MCSs) or supercells. However, even local systems such as multicell storms or single-cell Cb can produce some of these severe weather elements. Considering some well-established criteria for severe weather identification, it can be seen that they are relatively strict (Púčik et al., 2015, 2019), involving hail larger than 2 cm, wind gusts above 25 ms^{-1} and flash floods. In agricultural terms, a dense hail with diameters <10 mm in the blooming season or just before harvest can produce significant damage (Changnon et al., 2009). Additionally, it can indirectly endanger human life, causing traffic accidents. Heavy rain does not need to be large in total quantity to cause harm if the local intensity is high and it can thus temporarily flood the area (Cipolla et al., 2020; Gaál et al., 2014). Wind gusts pose elevated risks to structures, trees and any outdoor activities, and their reach is several tens of kilometers ahead of the storm (Klingle et al., 1987; Mohr et al., 2017). Active monitoring of these thunderstorm systems can be accomplished using remote sensors, such as radars, satellites, and a lightning detection network. Nevertheless, it is difficult to obtain good radar coverage in most regions due to the limited range and various sampling frequencies of radars, as well as their overall cost (Punge et al., 2016). Additionally, the frequency of satellite imaging is still relatively low to capture short-lived systems (Punge et al., 2014). Thus, lightning measurements are the only data source that has large spatial coverage and sufficiently high temporal resolution (1 s). Many convective storms are accompanied by lightning strikes, which are the main feature of storms over land (Àvila et al., 2010). The number of lightning strikes per storm generally depends on the concentrations of ice crystals and graupel and on the updraft intensity. When the updraft is sufficiently strong and a cloud contains both ice crystals and graupel, the non-inductive charging mechanism is triggered, and electrification (i.e., production of lightning strikes) will occur (Betz et al., 2009b; Mazzetti and Fuelberg, 2017; Takahashi, 1978). Depending on the strength of the updraft, lightning activity can increase or decrease, providing us with information on the development and intensity of a system.

The goal of this research is to provide comprehensive analysis of spatial and temporal hail properties over Croatia in present and future climate. Further, a link with synoptic and mesoscale conditions will be made. Finally, new thunderstorm intensity index (TSII) will be developed, verified, and applied to obtain spatially homogeneous coverage and climatology of potentially severe thunderstorms over Croatia.

2. Data and methods

To adequately analyze the hail distributions and properties in Croatia, several types of data were used. The first data set contains hail observations collected from weather stations from 186 weather stations located throughout the region of Croatia for a period of roughly 50 years, depending on the station. Data ware obtained from Croatian Meteorological and Hydrological Service (DHMZ). Using the standardized data retrieval approach, we obtained 7925 data points in space and time and used them as the main source of data. The second data set used is the ECMWF reanalysis ERA5 (Copernicus Climate Change Service (C3S), 2017), which has a horizontal resolution of 0.25° and is used to determine objectively defined weather patterns related to hail as well as instability indices (most unstable CAPE, K index, lifted index), deep layer sheer, and freezing level height to investigate relations to hail on the mesoscale level.

Further, using same objectively defined weather pattern algorithm, we analyzed simulations of the climate models from the EURO-CORDEX initiative using combinations of 4 global and 3 regional climate models to analyze future changes in hail patterns related to synoptic drivers in the future (Jacob et al., 2014). Additionally, lightning data acquired from Lightning Detection Network in Europe (LINET) (Betz et al., 2009a) was used for development, verification and climatological assessments of TSII. To support the verification process, additional data from DHMZ database for rain, wind and waterspouts, related to NE Adriatic region, were also used.

Hail analysis includes interannual, annual, seasonal, and diurnal scales as well as spatial analysis. Trends were computed on 28 selected stations with uninterrupted measurements for period of 1964–2019 where hail days, duration and hail intensity were considered. Additionally, hail days were used to determine synoptic forcing and the assessment of future climate, while hail cases were used to inspect mesoscale relations and relations to TSII.

Development of TSII index is based on previous method (lightning jump) which uses a set of mathematical operations that measure lightning behavior in shorter time intervals (1–5 min) over several steps (Schultz et al., 2009; Gatlin and Goodman, 2010; Chronis et al., 2015). One usually defines the storm center using some type of storm-tracking algorithm and area of influence, within which lightning strikes are collected in each timestep, is defined. The final steps include: (i) computation of the trend in the number of lightning flashes between several consecutive time steps, (ii) calculation of the standard deviation of several consecutive trends, (iii) the trend(s) is(are) compared against the standard deviation from the previous step and (iv) iteration of the procedure by moving one step forward. Finally, when a trend exceeds a predefined threshold of the standard deviation (the most common threshold is two sigma), it is considered that a lightning jump occurred. Although mathematically the same, the key difference between lightning jumps and the TSII is in lightning data retrieval. TSII does not require the use of a storm tracking algorithm and influence radius, because it observes a storm passing over a predefined grid on the ground, therefore, this approach offers a new angle. The storm is divided into arbitrarily small segments (i.e., a predefined grid), allowing identification of the potential impacts of the storm on a particular grid point and at a particular point in time. Since the TSII algorithm is computed independently for each grid point, severe storms will leave a trail of the TSII, revealing the area over which the most active part of the storm has passed. In other words, the TSII is a diagnostic tool that, in retrospect, highlights areas over which a storm was the most active. Additionally, due to the current computational settings, the TSII is a binary (yes/no) index that obtains a positive value (e.g., TSII = 1) if the storm intensifies rapidly, while otherwise TSII equals zero.

3. Results and conclusions

The preliminary analysis determined that the data on hail can be divided into three areas, according to the type of annual cycle. Thus, out of a total of 186 stations, 113 stations were identified as belonging to the "summer" type, 31 stations were associated with the transitional type, and remaining 42 stations were of the "winter" type. The "summer" type are the stations that predominantly recorded hail in the warm part of the year (May–October), while the "winter" stations are those that have more frequently measured hail in the cold part of the year (November–April). The transitional type has no preferences. Basic data analysis suggests that in Croatia hail occurs throughout the year, which is a new information considering that previously most research was concentrated on the warm part of the year, thus using only "summer" type stations (Gajić-Čapka and Zaninović, 1993; Počakal et al., 2009; Počakal et al., 2018).

Diurnal cycle also shows significant differences. While the "summer" type follows the so far well-accepted form with a maximum in the afternoon hours, the transitional type records significant hail activity already in the morning hours, with a maximum around noon. The "winter" type, on the other hand, records the maximum of hail occurence as early as 8 a.m. Central European Time (UTC + 1), and hail activity remains pronounced until the late evening hours.

The interannual trend shows great variability for all three types of stations, and the variability dynamics do not coincide with each other for any of the considered elements (hail days, duration, and hail intensity). From these datasets, the trend was calculated for the whole Croatia as well as for the individual areas and individual seasons. Regarding hail days, the obtained results indicate a negative trend for the whole Croatia, for which the „summer" and „winter" type of stations are responsible, while the transitional type does not show any significant changes. Further analysis revealed that these trends are the result of a reduction in hail activity in the summer season for the „summer" type and in the summer and autumn seasons for the „winter" type of stations, within which there is an indication of a negative trend in the spring season.

The analysis of synoptic systems over the Croatian teritorry, in the context of hail, shows the dominance of cyclonic types, which is expected considering that these systems provide a large source of instability, higher CAPE values and abundant moist air. By combining the general distribution of weather types and those associated with hail, the percentage of hail in a particular weather type is obtained, and this value was used to assess hail in the future climate. The result of that procedure showed that, compared to the reference period (1971–2000), hail activity decreases by up to 8% as we move towards the end of the 21st century. The ensemble of climate simulations also shows a systematic reduction of the cyclonic type of weather, and an additional weakening of deep cyclonic systems, which is the main reason for the recorded decrease in hail in the future, given that the quasi non gradient field is difficult to distinguish in the used climate models at 12.5 km resolution.

The mesoscale conditions for hail, obtained from the ERA5 reanalysis, confirm that hail forms in very unstable atmospheric conditions (CAPE 650 Jkg^{-1}, LI -4.8°C, KI 31°C) with DSL 14.8 ms^{-1}, and the freezing level height 2500 m. There are certain differences between the individual station types, the most prominent of which are those between the "summer" and "winter" types. As the bulk of hail in the "winter" type is located within the cold part of the year, when the general potential and capacity for moisture and instability is reduced, the lowest CAPE values are also recorded. This lack of atmospheric instability is compensated by elevated DSL values, which is consistent with previous research (Púčik et al., 2017).

In the process of verifying the thunderstorm intensity index (TSII), data on rain, wind, hail and waterspouts recorded in the area of the northeastern Adriatic over a period of 11 years were used. The obtained results for rain (area of influence of 3 km) show a very good agreement between the trace of the TSII index and high values of intensity and total amount of rain. The comparison with wind also showed that environments within a large area of influence that had a TSII footprint, recorded significantly higher wind values, regardless of whether it was a coastal station or a land station. Hail also had a pronounced positive connection with the TSII footprint, and in the northeastern Adriatic about 68% of hail was associated with other products of deep convection within a 15 km area. In the extended analysis (over Croatia), it was found that this percentage is even higher (about 74%), and if only the warm part of the year or the strong intensity of hail is observed, these percentages approach 90%. This confirmed that the TSII trace really represents the systems and environments within which potentially extreme or extreme events are recorded. A somewhat unexpected benefit of the proposed method is the ability to detect local convective systems that still have potentially extreme effects. Through the results it was shown that the systems that have a trace of TSII smaller than 90 km^2, still have very pronounced precipitation amount values, are still successfully associated with the occurrence of hail and strong wind gusts and are formed in equivalently unstable atmospheric conditions.

As the method allows monitoring the track of TSII at high spatial and temporal resolution, the obtained results are suitable for model verification, supplementing other climatological studies, but also as an independent tool for assessing the risk of potentially extreme events. Through the results of this work, the daily and annual trends were also shown, which are in good agreement with those obtained for hail, but also in other hail surveys based on radar estimates in Slovenia (Stržinar and Skok, 2018).

Further to the above, the importance of dense and detailed hail measurements cannot be emphasized enough. The observed spatial and temporal characteristics of hail are a clear sign that it is a highly variable phenomenon. The latest technologies and knowledge finally make it possible to start modeled hail research in terms of forecasting (Brimelow et al., 2002; Adams-Selin and Ziegler 2016; Malečić et al., 2022b). Therefore thorough analyzes of the spatial and temporal characteristics of hail, as well as more detailed and dense data sources, will be extremely important for such research. And for the areas in the Southeastern Europe that will not have them, such as currently Bosnia and Herzegovina, Montenegro, Albania (Punge and Kunz, 2016) and other areas, the TSII index proposed in this paper could serve as a spatially filled replacement.

SADRŽAJ
CONTENTS

Hrv. meteor. časopis	Vol. 56	p. 1-216	ZAGREB	2023